University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Biological Systems Engineering--Dissertations, Theses, and Student Research

Biological Systems Engineering

11-2010

REMOVAL OF LOW DENSITY SEDIMENTS BY VEGETATIVE FILTERS

Brent M. Hall
University of Nebraska-Lincoln, brent.hall@huskers.unl.edu

REMOVAL OF LOW DENSITY SEDIMENTS BY VEGETATIVE FILTERS

by

Brent M. Hall

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Agricultural and Biological Systems Engineering

Under the Supervision of Professor Dean E. Eisenhauer

Lincoln, Nebraska

November, 2010

REMOVAL OF LOW DENSITY
SEDIMENTS BY VEGETATIVE FILTERS

Brent M. Hall, M.S.
University of Nebraska, 2010

Advisor: Dean E. Eisenhauer

The use of vegetative filter strips (VFS) is a longstanding best management practice for the removal of sediment and other pollutants from overland flow. Many attempts have been made to model the effectiveness of a VFS based upon soil, vegetation, and sediment properties, and also upon flow conditions, but little work has been done to investigate the reliability of the existing models when considering sediments, such as microbial pathogens, that have a lower density than the mineral sediments used for development of the models. The objectives of this study were to: 1) quantify the ability of a VFS to remove low density sediments from overland flow, and 2) assess the impact of infiltration on the effectiveness of a VFS. A 0.3 meter wide by 5 meter long artificial VFS with a controllable rate infiltration system was constructed in a variable slope flume. Tests were conducted to investigate VFS effectiveness for 3 inflow rates and 3 infiltration rates, and each condition was also modeled with the computer program VFSMOD (Muñoz-Carpena et al., 1999) for comparison between experimental and modeled results. Flume results ranged from 75% to 93% of sediment trapped by the artificial VFS, based upon flow conditions, while modeled results were significantly higher, ranging from 98.6% to 100% of sediment trapped by the VFS. However, an unknown proportion of the observed difference between the observed and modeled results is likely due to the observations that the experimental setup violated the

assumption that no bed load transport takes place within the VFS. The water inflow rate had a significant effect upon VFS effectiveness, but infiltration rate was an insignificant factor in VFS effectiveness, most likely because of the relatively low percentage of inflow water that infiltrated within the artificial VFS.

To my loving wife, Kyla,
without whose support this project
would not have been possible.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1 Vegetative Filter Strip Use

A vegetative filter strip (VFS), buffer strip, or filter strip is a band of vegetation between a field and the receiving waterway that serves to slow surface runoff and remove sediments, nutrients, and other contaminants from overland flow (ASABE, 2007). VFSs have long been used to reduce sedimentation of waterways caused from soil erosion (Tollner et al., 1976) and are a widely accepted best management practice (BMP) for controlling suspended sediments (Dillaha et al., 1988). Generally VFSs reduce sediment discharge to receiving waters by at least 80%, often showing results of 95% or greater, depending upon filter and flow conditions (Abu-Zreig et al., 2001; Blanco-Canqui et al., 2004; Coyne et al., 1995; Dillaha et al., 1988; Hayes et al., 1984). Dillaha et al. (1988) suggest two major mechanisms for the suspended sediment removal functions of VFSs: infiltration and sedimentation caused by reduced flow velocity within the filter. Both infiltration, which reduces flow volume, and the reduced flow velocities resulting from the increased flow resistance provided by the vegetation serve to reduce the sediment transport capacity of the flow, thereby leading to deposition of suspended sediments if the inflow concentration is higher than the new transport capacity. Infiltration also serves to reduce the amount of both the dissolved and suspended constituents in overland flow when the components are transported into the soil profile with the infiltrating water.

Not only are VFSs valuable for removing mineral sediments from overland flow, but they have also been used to improve water quality by reducing nutrient and microbial contaminants from overland runoff (Fajardo et al., 2001; Lim et al., 1998; Tate et al., 2006). Microbial pathogen removal from overland flow by a VFS poses special problems because of their small size and low density when compared to mineral sediment. Several studies have been performed to investigate the effectiveness of VFSs in removing microbial organisms from overland flow.

Fecal coliform bacteria removal by a VFS has been studied with widely varying results. Coyne et al. (1995, 1998) reported a 43 to 74% fecal coliform reduction with a VFS in one study with land-applied poultry waste and a 74 to 91% reduction with a VFS in another study with poultry waste incorporated into the soil. A 0.3 to 3.1 $\log_{10}$ mass reduction of *Escherichia coli* per meter of vegetative filter was reported by Tate et al. (2006), and Lim et al. (1998) recounted 100% fecal coliform removal. Both Tate et al. (2006) and Lim et al. (1998) attributed the VFS efficiency partially to high infiltration within the filter (98.2% of inflow in the case of Lim et al.). Tate et al. (2006) reported that VFS efficiency was greater under conditions of lower inflow rates and more dense vegetation, suggesting that a limiting factor for VFS efficiency is the sediment transport capacity of the overland flow. Fajardo et al. (2001) determined that VFSs were not effective for the removal of bacterial constituents based upon bacterial concentrations, which agrees with the determinations of Coyne et al. (1995, 1998) that, despite the mass reduction of fecal coliforms, the runoff from the VFS did not meet water quality standards for concentration. Making the assumption that, due to their low density, there is essentially no deposition of free bacteria in VFSs, Tyrrel and Quinton (2003) determined that any reduction in bacterial concentrations that occurs without complete infiltration (no outflow from the VFS) is the result of interaction between bacteria and soil particles.

Fewer studies have examined the applicability of using a VFS to remove protozoan pathogens such as *Cryptosporidium parvum* from overland flow. Tate et al. (2004) hypothesized that *C. parvum* should be removed to a greater degree than *E. coli* because of its greater size and more spherical shape that would allow for it to settle more quickly than *E. coli*. Atwill et al. (2002) reported a 1.0 to 3.1 $\log_{10}$ reduction of *C. parvum* oocysts per meter of VFS, while Tate et al. (2004) reported a mean oocyst reduction rate of 1.18 to 1.44 $\log_{10}$ (dependent upon filter slope), and Trask et al. (2004) tested a wide range of conditions and reported oocyst recovery rates in the outflow from a VFS of 0.6 to 27.2% of the introduced amount. Both slope and rainfall/inflow rate were negatively correlated with VFS efficiency (Tate et al., 2004; Trask et al. 2004) as was soil bulk density (Atwill et al., 2002). Ultimately Tate et al. (2004) concluded that infiltration was the primary mechanism for *C. parvum* removal by a VFS, and Trask et al. (2004) determined that VFSs are an effective BMP for removing *C. parvum* oocysts from overland flow.

1.2 VFS Modeling

Through a series of laboratory and field studies a set of equations, commonly called the University of Kentucky (UK) model, was developed to predict the sediment removal efficiency of vegetative filter strips (Barfield et al., 1979; Haan et al., 1994; Hayes et al., 1979, 1984; Tollner et al., 1976, 1977, 1982). The UK model describes the fraction of sediment trapped as it flows through a VFS based upon filter characteristics, the hydraulics of flow, and inflow water and sediment loads. The basic empirical prediction equation for fraction of sediment trapped, i.e. the trapping efficiency, Tr, by a VFS is a function of the Reynolds number, Re, and the particle fall number, N_f, as follows:

(1)

with

$$R_e = \frac{\quad}{\quad} \qquad (2)$$

and

$$N_f = \frac{\quad}{\quad} \qquad (3)$$

where V is the overland flow velocity, d is the flow depth, L is the length of the VFS, V_s is the particle settling velocity, ν is the kinematic viscosity, and R_s is the spacing hydraulic radius. R_s is calculated from the depth of flow and the vegetation spacing, s, as:

$$R_s = \frac{\quad}{\quad} \qquad (4)$$

Flow velocity and depth are calculated from the continuity and Manning's equations:

(5)

$$V = \frac{\quad}{\quad} R_s^{2/3} S_o^{1/2} \qquad (6)$$

where q is the flow rate per unit width, n is the Manning's roughness coefficient, and S_o is the bed slope of the VFS. Equation 1 assumes no infiltration occurs within the VFS, giving the sediment reduction due solely to sedimentation.

For conditions with very high sediment inflow rates and/or multiple inflow events a wedge of sediment develops at the upslope end of the VFS, builds until it inundates the vegetation, and then deposits down through the VFS. A complete set of equations for modeling this situation was developed (Hayes et al., 1984; Tollner et al., 1977).

Early development of the UK model occurred under conditions with no infiltration, but later developments assumed a steady state infiltration rate, causing a linear decrease in the flow rate throughout the VFS. Hayes et al. (1984) verified the model in both laboratory and field tests, although they suggest that more realistic modeling of infiltration may have provided even better results. Two later developments outlined in Haan et al. (1994) provide: a correction to allow for re-entrainment of deposited sediments, and a method for adjusting the efficiency of a VFS to account for the effects of infiltration based upon the assumptions that any difference in flow between the VFS inlet and outlet is due to infiltration, and that any sediment in infiltrating water is trapped on the bed of the VFS. Using a different experimental setup and much lower sediment inflow rates, Deletic (1999) concluded that the University of Kentucky model over-predicted the effectiveness of at VFS, particularly for small particles, which agrees with the observations by some of the model developers that a VFS does not effectively remove mineral density particles smaller than 0.004 mm from overland flow (Haan et al., 1994). In an attempt to better match her observed VFS efficiencies, especially for smaller sediments, which would have a lower fall number, Deletic (2001) proposed a different equation for predicting the trapping efficiency, Tr, of a VFS based solely upon the particle fall number (N_f, Equation 3) used in the UK model:

$$Tr = \overline{\qquad\qquad} \tag{7}$$

In order to automate the calculations of the University of Kentucky model and to improve upon its flow assumptions by linking it to hydrologic and hydraulic calculations, Muñoz-Carpena et al. (1999) developed the computer program VFSMOD. VFSMOD combines the University of Kentucky sediment filtration model with models to solve for overland flow hydraulics with a kinematic wave routing solution and the Green-Ampt infiltration model. Muñoz-Carpena et al. (1999) validated VFSMOD with field results from 27 runoff events, and it was further tested and found to be effective in predicting VFS performance by Abu-Zreig et al. (2001). Sensitivity analysis by Muñoz-Carpena et al. (1999) found that the most important parameters for modeling a VFS are the saturated hydraulic conductivity and initial water content of the soil, the sediment characteristics (settling velocity), and the spacing of the vegetation. This agrees with the conclusion cited earlier (Atwill et al., 2002; Dillaha et al., 1988; 2002; Lim et al., 1998; Tate et al., 2004, 2006) that infiltration is a major factor influencing VFS performance. Through a simulation study Abu-Zreig (2001) determined that filter length was the most important of five investigated factors and soil type had only a minor effect on VFS performance. However, the saturated hydraulic conductivity of the three soil types simulated by Abu-Zreig (2001) only ranged over one order of magnitude, which is a much smaller variation than would reasonably be expected under field conditions. Using her own model (which also used a kinematic wave sub-model and the Green-Ampt equations to solve the hydrology components), Deletic (2001) performed a sensitivity analysis and found that filter length was the most important factor when considering sediment removal, followed by grass density and soil saturated hydraulic conductivity. These critical factors agree with the observations of others (Atwill et al., 2002; Dillaha et al., 1988, Tate et al., 2004, 2006) that filter length and soil properties, especially hydraulic conductivity (i.e. infiltration rate, which can have a significant effect upon runoff volume/rate), are extremely important in VFS performance.

1.3 Microbial Properties

Cryptosporidium parvum oocysts are spherically shaped with an average diameter around 5 μm (Dai and Boll, 2006; Medema et al., 1998; Young and Komisar, 2005). The density of *C. parvum* oocysts has been reported to be between 1009 and 1080 kg m^{-3} (Dai and Boll, 2006; Medema et al., 1998; Young and Komisar, 2005). However, Young and Komisar (2005) reported that the majority of the oocysts in the lower part of the density range (< 1040 kg m^{-3}) were either not intact or nonviable. *Giardia lamblia* cysts are elliptically shaped with an average diameter around 10 μm, an average eccentricity of 1.3 to 1.5, and average densities of 1013 to 1036 kg m^{-3} (Dai and Boll, 2006; Medema et al., 1998). Medema et al. (1998) and Dai and Boll (2006) both found that Stokes' law provides an adequate estimation of the settling velocity of both *C. parvum* oocysts and *G. lamblia* cysts, with rates of around 0.8 μm s^{-1} and 0.4 μm s^{-1}, respectively (Dai and Boll, 2006).

Oocysts and cysts have been shown to have surface charges ranging from negative to neutral (Butkus et al., 2003; Dai and Boll, 2006; Searcy et al., 2005). While Dai and Boll (2003) suggest that the negative charge of the oocysts and cysts prevent them from attaching with soil particles in solution, others have demonstrated that oocysts and cysts attach to particles in solution, thereby increasing their settling velocity (Medema et al., 1998; Searcy et al., 2005; Young and Komisar, 2005). Despite this attachment, Medema et al. (1998) and Young and Komisar (2005) both concluded that it was unlikely that significant sedimentation of oocysts and cysts would occur in natural environments. But, Searcy et al. (2005) dispute this, claiming that oocysts are likely to be removed from suspension as a result of sedimentation via attachment to soil particles. When evaluating *Cryptosporidium* transport in streams, Searcy et al. (2006) determined that the association between sediment particles and oocysts increased oocyst deposition rates substantially enough that the interactions should be considered during transport modeling.

1.4 Objective

The first goal of this study was to quantify the ability of a VFS to remove low density particles from overland flow. A comparison was made of these results with the predicted results from the existing VFS modeling equations and software, such as VFSMOD. As suggested by Tyrrel and Quinton (2003), this information will help to determine if the current VFS modeling and design approaches can be applied to microbial pathogens when the appropriate properties of the microbes are considered, or if more research is needed to provide more accurate equations to better predict the removal of pathogenic organisms by a VFS. The properties of the microbial sediments could be key factors in the success of using a VFS for removing pathogens from runoff. Specifically, the effect of the settling velocity on the performance of a VFS was investigated by using low density plastic particles as a surrogate for the microbial sediments.

A second goal of this study was to determine the impact of infiltration upon the sediment removal efficiency of a VFS. Infiltration has the potential to greatly change the hydraulics of overland flow, which should in theory lead to an increase in VFS efficiency.

Chapter 2. Materials and Methods

2.1 Artificial Vegetative Filter Strip

Laboratory tests were conducted using an artificial vegetative filter strip (VFS) and low-density sieved sediments under varying inflow and infiltration rates. The artificial VFS was constructed within a flume with an infiltrating bottom by placing stainless steel cylindrical rods through the floor of a plexiglas flume, making a filter of rigid vegetation. The artificial vegetation, 16d nails, had a height of 8 cm, a diameter of 0.42 cm, and was arranged in an isometric grid pattern with a spacing of 2.5 cm (Figure 1). The spacing of 2.5 cm is less than the average grass spacing of 3.4 cm measured within a VFS in Nebraska by Helmers et al. (2005a).The constructed VFS measured 30.5 cm wide by 5 m long and was set to a 1% slope.

2.1.1 Infiltration System

The challenge of realistically modeling infiltration within a flume is to create a system that allows the infiltration rate to decrease continuously with time and asymptotically approach a constant rate. Jobling and Turner (1967) designed a system to accomplish this with point infiltration ports connected to containers specially designed to control the infiltration rate. The containers were designed with an outlet hole in the base that was sized smaller than the inflow line, allowing the container to slowly fill. The radius of the containers increased continuously with height, increasing the volume per unit depth with height, leading to a slowly decreasing infiltration rate that reached a constant rate when the container filled and overflowed.

For this experiment an infiltration rate control system was designed to allow simulations to mimic the infiltration pattern predicted using the Green-Ampt equations as presented by Chow et al. (1988) for instantaneously ponded conditions as:

$$K_s t = F - MS_{av} \, ln\left(1 + \frac{}{}\right) \tag{8}$$

$$f = K_s + \frac{}{} \tag{9}$$

where K_s is the saturated hydraulic conductivity (cm hr^{-1}), t is the time since infiltration began (hr), F is the cumulative infiltration (cm), M is the initial soil water deficit, $\theta_s - \theta_i$, (dimensionless), S_{av} is the average suction at the wetting front (cm), and f is the infiltration rate (cm hr^{-1}). All modeling and calculations were performed with M = 0.147 and S_{av} = 27.1 cm.

In order to mimic the predicted infiltration pattern two control measures were instituted on twenty-four infiltration ports equally spaced throughout the artificial VFS. The first flow control measure was a needle valve with a vernier scale (Nupro Corp. #B-4L2-MH) attached to each infiltration port by tubing, allowing precise, repeatable flow control settings. Tubing directed the outflow from each valve into an upward opening cone constructed of a series of schedule 40 PVC pipes of increasing diameter and corresponding schedule 80 reducers (Table 1, Figure 2). The cone was designed so that, as the cone filled, the decreasing hydraulic head across the needle valve caused a decrease in the flow rate. By varying the number of infiltration ports open and the setting on the needle valves, infiltration can be modeled for conditions controlled by a saturated hydraulic conductivity ranging up to 7 cm hr^{-1}.

2.1.2 Flow Introduction

Municipal water was used as the source for the VFS inflow. Flow rates were determined using a stop watch and in-line flow meter. The flow was introduced to the flume upstream of the artificial VFS through a manifold that distributed the flow across the entire width of the flume. Sediment was introduced into the flume between the flow distribution manifold and the artificial VFS using an adjustable rate dry material feeder (AccuRate, Inc.).

2.2 Sediment

Granular plastic particles (Opti-Blast, Inc. #T-2) were used as the low density sediment. Manufacturer specifications list the particles with a specific gravity of 1.5 and a size range of 0.420 – 0.595 mm (U.S. standard sieve sizes 30 – 40). Glass beads (Kramer Industries, Inc.) of the same size with a specific gravity of 2.5 (approximately mineral density) were also used for some tests. The theoretical settling velocity (V_s, m s^{-1}) of each sediment was calculated using Stokes' Law as given by Dai and Boll (2006) and Medema et al. (1998) as:

$$V_s = \frac{\qquad}{\qquad} \tag{10}$$

where g is the acceleration of gravity (taken as 9.81 m s^{-2}), ρ_p is the particle density (kg m^{-3}), ρ_l is the liquid density (taken as 998 kg m^{-3}), d is the particle diameter (taken as the geometric mean of the screen openings (0.5 mm or 0.0005m), m), and μ is the dynamic viscosity of the liquid (taken as 0.001 N s^{-1} m^{-2}). The calculated settling velocities for the low density plastic sediment and the mineral density glass sediment were 0.068 m s^{-1} (6.8 cm s^{-1}) and 0.204 m s^{-1} (20.4 cm s^{-1}), respectively.

The particle settling velocities of both sediments were measured using high definition video at 30 frames per second and a clear settling tank. The observed mean ($n = 100$) settling velocities of the plastic and the glass were 2.7 and 7.4 cm s^{-1} with standard deviations of 1.1 and 0.8 cm s^{-1}, respectively. These observed settling velocities are significantly lower ($\alpha = 0.05$, $P = 0.0000$ for both) than the predicted settling velocities from Stokes' Law, suggesting a smaller mean particle diameter than assumed and/or an increased particle drag resulting from a non-spherical shape.

2.3 Flow Concentrations

Inflow sediment concentration was determined immediately before, twice during, and immediately after each experiment by measuring the water inflow rate and amount of sediment collected from the dry feeder outlet in a one minute time period. Outflow samples were collected in a one liter bottle from the end of the artificial VFS to determine sediment concentrations leaving the VFS. Concentrations were determined by gravimetrically determining the water volume and measuring the sediment mass by filtering the collected samples through a 20-25 µm filter (Whatman, Grade 4), then drying and weighing the filter. As a secondary measure of the artificial VFS performance the flume outflow was filtered by a nylon woven mesh screen with 300µm openings (McMaster-Carr, #9318T45) to collect all sediment passing through the filter. After each experiment the flume was flushed free of all accumulated sediment, which was collected by a second screen which filtered the effluent from the VFS.

2.4 Experimental Parameters

An inflow sediment concentration of 0.5 g L^{-1} was used for all experiments. This concentration fits within the range of 0.15 – 2.87 g L^{-1} observed flowing into a VFS by Helmers et al. (2005a) for mineral sediments. A combination of three different inflow rates and three different infiltration rates were tested, giving nine experimental treatments, each of which was repeated three times (Table 2). The inflow rates tested are given as unit rates and fall within or slightly above the field inflow rates observed by Helmers et al. (2005b). The infiltration rates were specified by the saturated hydraulic conductivity (Ks) parameter in the Green-Ampt equation. As a check of the experimental setup, a triplicate of one set of experimental conditions (no infiltration, inflow of 2 L m^{-1} s^{-1}) was run with glass beads of mineral density since these conditions and the sediment matches the work done by Tollner et al. (1976) during early modeling development.

2.5 Experimental Procedures

Before each experiment the water inflow rate and infiltration valve settings were set for the particular test conditions. A drain valve in the infiltration line allowed the infiltration valves to be set for a particular rate without actually allowing flow into the infiltration cones. The sediment inflow rate was also set and verified by collecting the feeder output for a timed period. At the start of the experiment the sediment was allowed to flow into the VFS and the drain valves in the infiltration line were closed, starting the decrease in the infiltration rate. Experiments were run for thirty minutes, and VFS outflow samples were collected every five minutes. Inflow sediment concentration was determined every ten minutes by measuring the water and sediment inflow rates. Flow depth and water inflow rate were also measured three times throughout each experiment. After each experiment the VFS effluent screen was changed and the VFS was flushed free of all deposited sediment.

2.6 VFSMOD Simulation

VFS simulations of the experimental conditions were performed using the software VFSMOD-W v. 5.1.7 (Muñoz-Carpena et al., 1999). All artificial VFS parameters and experimental treatments were used as inputs for the flow, vegetation, soil, and sediment files. In order to account for the observed settling velocities the particle diameters that resulted in equivalent settling velocities were calculated from Equation 9, giving a particle diameter of 0.0003 m (0.3 mm) for both sediments. Additional inputs required are listed in Table 3.

2.7 Statistics

For the purpose of this study, vegetative filter strip trapping efficiency (or just efficiency), E, is defined as the percentage of sediment removed from overland flow by the VFS as follows:

$$E = \frac{-}{\quad} \text{ x } 100\% \tag{11}$$

where M_i and M_o are the mass of sediment in and out of the VFS, respectively.

Statistical calculations were performed with SigmaPlot 11.0 (Systat Systems, Inc) and a spreadsheet. Infiltration system verification involved calculating the root mean square error (RMSE) and the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) as:

$$RMSE = \qquad (12)$$

$$NSE = 1 - \qquad (13)$$

where x_o, x_p, and are the observed, predicted, and mean values, respectively. Comparisons involving the VFS efficiency were evaluated with t-tests, and an analysis of variance test was performed to analyze the treatment effects.

Chapter 3. Results and Discussion

3.1 Infiltration System

An equation was developed to predict the flow rate through the needle valves by measuring the cumulative flow for a timed period through a valve with a known pressure head and different valve settings. Data from 118 tests were used to develop a multivariable flow rate equation, Q_v (L min^{-1}), for the pressure head, p (cm of water), and valve setting, θ (turns open). The resulting equation,

(14)

had a very good fit to the data ($R^2 = 0.96$) and was used to model the infiltration within the artificial VFS.

The infiltration system was tested and verified by measuring the cumulative flow in a given period of time. The results for the modeling with an infiltration rate controlled by a saturated hydraulic conductivity equal to 1 cm hr^{-1} can be seen in Figure 3 along with the prediction of the cumulative inflow from both the valve flow equation and the Green-Ampt infiltration model. Valve flow modeling allowed for variation in the number of valves used and the opening of the valves in order to obtain the flow rates required to match the Green-Ampt model. Overall there was very good agreement between the observed results and the prediction from the valve equation, with a root mean square error of 0.121 cm of infiltration and a Nash-Sutcliffe efficiency of 0.95 for the 25 observations. Figure 4 shows the results of similar modeling controlled by a saturated hydraulic conductivity of 0.1 cm hr^{-1}, which also showed good agreement with predicted values from 49 observations as demonstrated by a RMSE = 0.043 cm of infiltration and a NSE = 0.97.

The infiltration system functioned well for the experimental parameters, but there was a limitation discovered for VFS inflow rates lower than those tested. Because of the point nature of the infiltration ports and the initially high infiltration rates, lowering the VFS inflow rate resulted in overland flows at the lower end of the VFS being insufficient to keep the infiltration ports flowing, causing air to enter the infiltration tubing and preventing the infiltration of water.

3. 2 Filter Roughness

The Manning's n roughness coefficient was calculated for the artificial VFS from Manning's equation by using measurements of flow depth from the point gage and flow rate calculated from the inflow and infiltration rates. These parameters were used to calculate the spacing hydraulic radius and velocity using Equations 4 and 5, respectively, then Manning's n was calculated from Equation 6. The calculated mean Manning's n from 90 sets of measurements for the channel between the vegetation, as used in the UK model, was 0.00057 with a standard deviation of 0.000048. This is much lower than the value of 0.0072 determined for cylindrical media by Barfield et al. (1979). The Manning's n when considering the entire flume as a channel and accounting for the vegetation as roughness was calculated to be 0.00095 (n = 90) with a standard deviation of 0.000084, which is a very low value for Manning's n compared to those commonly used for overland flow, but the very smooth nature of the VFS materials (bed and artificial vegetation) leads to this very low roughness coefficient.

3.3 Artificial VFS Performance

Vegetative filter strip efficiency was measured with two independent methods for this experiment. One method calculated the mass introduced into the VFS by calculating the average dry feeder rate between consecutive sampling periods (10 minute intervals). Similarly, the mass of sediment passing through the VFS was calculated from the average sediment concentration between consecutive outflow samples (5 minute intervals) and the outflow rate predicted by subtracting the infiltration rate modeled by the valve flow equation from the inflow rate. For the second method the efficiency of the VFS was calculated directly from the sediment captured by the screen at the end of the filter during the run and also after the run when the filter was flushed clean of sediment.

The observed mean artificial vegetative filter strip efficiency ranged from 76.6% to 93.4% for all low density sediment treatments investigated when calculating efficiency from the outflow samples, as is shown in Figure 5. The three replicates of each treatment showed a very good agreement, as measured by the standard deviation of the measurements, ranging from 0.4% to 2.2%. For all treatments except one, mean VFS efficiency was slightly lower when calculated using the masses captured by the outflow screen, ranging from 74.5% to 91.4%, with the one exception having equal means when using the two different calculation methods. Of the nine treatments, the difference between the two efficiency calculation methods was only significant (paired t-test, difference of means, $\alpha = 0.05$) for one condition (inflow = 3.3 L m^{-1} s^{-1}, saturated hydraulic conductivity = 0 cm hr^{-1}, $P = 0.003$), providing verification of the results. The differences in calculated mean VFS efficiency are most likely due to a slight loss of sediment during the filter flush. The minor loss of sediments was a consequence of the higher flow volumes required to flush the accumulated sediment from the filter causing small amounts of flow to occasionally bypass the outflow screen.

All three replicates of the experiments with the mineral density glass beads were in agreement both between replicates and between efficiency calculation methods. Both measures for all three replicates showed 100% VFS efficiency when considering removal of the mineral density sediments. These results match well with the results that Tollner et al. (1976) used to develop the University of Kentucky (UK) model and the results also agree well with the VFSMOD predictions, but are significantly higher than the predicted results from the equation developed by Deletic ($\alpha = 0.05$, $P = 0.0000$) (Table 4).

When comparing the observed efficiency of the artificial VFS to the efficiency predicted by the UK model and VFSMOD the results were significantly different for the low density sediments. Both the UK model and VFSMOD predict VFS efficiency ranging from 98.6% to 100% sediment removal, compared to the maximum efficiency measured from the outflow samples of 93.4% (Table 4). A pairwise comparison of the outflow sample efficiencies with both the UK model and VFSMOD predicted efficiencies showed that all observed results from the artificial VFS were significantly lower than the predicted results (paired t-test, $\alpha = 0.05$, $P \leq 0.0017$ for all 18 comparisons). The equation developed by Deletic (2001) predicted a significantly lower VFS efficiency ($\alpha = 0.05$,

$P \leq 0.0074$ for all 9 comparisons) than was observed in the experimental results, with predicted efficiencies ranging from 70.5% to 84.5%. Figure 6 shows the VFS trapping efficiency predicted from the UK model (Equation 1), the VFS trapping efficiency predicted from the equation developed by Deletic (Equation 7), and the observed efficiencies from the artificial VFS for the observed flow conditions. The Deletic equation was transformed for plotting with the UK model predictions by assigning a Reynolds number to a set of fall numbers and then calculating the UK model dependent variable ($Re^{0.82}\ Nf^{-0.91}$) and the predicted results from the Deletic equation. The Deletic equation is plotted independently, along with the experimental results, in Figure 7.

If the reported settling velocity of protozoan pathogens is considered when modeling the effectiveness of a VFS the results are much different. Using the experimental flow conditions observed and the reported settling velocities of 0.4 μm s^{-1} and 0.8 μm s^{-1} (Dai and Boll, 2006) the UK model predicted VFS trapping efficiency was 0.00%, while the Deletic equation predicts the VFS trapping efficiency to be 0.18% to 0.46%. While the models differ somewhat in their predictions, it can be concluded that, except for transport with infiltrating water, there is essentially no removal of particles with such low settling velocities, which agrees with the conclusions of previous researchers (Tyrrel and Quinton, 2003) .

One possible reason for the lower than predicted sediment removal efficiencies of the artificial VFS used in the study (compared to VFSMOD and the UK model) is its bed characteristics. The flume and VFS bed were constructed of plexiglas with few to no surface irregularities, as demonstrated by the very low Manning's n roughness coefficient. The smoothness of the surface prevents any interactions between the sediment particles and the surface that may serve to impede particle movement or trap the particles completely. During experiments with the low density sediment this was observed as sediment bed load movement through the VFS, although no such sediment bed load movement was observed with the higher density glass beads. This bed load transport is in conflict with an assumption in the UK model that there is no sediment movement as bed load beyond the wedge that forms at the head of the VFS. A small wedge did begin to form at the head of the VFS during each experiment, but the total sediment mass introduced into the filter was not sufficient to change the hydraulics of the VFS or the slope of the bed, much less to form a complete, vegetation inundating wedge. The lack of deposition within the VFS also precluded the need to correct the UK model for re-entrainment of trapped sediment. This discrepancy could be a significant factor in the differences between the observed and predicted performance of the artificial VFS.

In order to determine the effects of the specific treatment types upon the efficiency of the artificial VFS an analysis of variance test was run comparing infiltration and inflow rates. The results show that there was a significant ($\alpha = 0.05$) difference in the efficiency of the VFS between the inflow rates ($P < 0.001$), but the infiltration rate had an insignificant ($P = 0.449$) effect on VFS efficiency. Pairwise comparisons between the inflow rates showed that all three inflow rates produced significantly different VFS efficiencies from one another ($P \leq 0.012$). The relative effects of inflow and infiltration on VFS efficiency can clearly be seen in the results in Table 4 and in Figure 5, with infiltration actually showing an unexpected but insignificant negative effect on VFS performance for the higher flow rates.

One possible explanation for the dominance of inflow over infiltration as influencing factors on the VFS efficiency is the low amount of water removed from overland flow by infiltration within the extent of the VFS, ranging from 2 – 18% (Table 5). The adjustments for infiltration to the UK model outlined by Haan et al. (1994) were investigated and found to have very little effect upon the predicted VFS efficiency. The average increase in VFS efficiency was 0.3%, with a maximum of 1% increase. This is likely due to the very low percentage of inflow that infiltrated into the bed of the VFS. Previously reported infiltration percentages of VFSs on silt loam soil vary from around 25% for 4 m of VFS (Blanco-Canqui et al., 2004), and 6% for a 4.6 m VFS (Dillaha et al., 1988), to greater than 98% for a 6.1 m VFS (Lim et al., 1998), 26-86% for a 13 m VFS (Helmers et al., 2006), and 76 – 88% for a 4.5 m VFS (Coyne et al., 1995; 1998). The observed infiltration in this experiment fit within the wide range of infiltration percentages possible in natural conditions, but may not be high enough for ideal VFS construction.

Figures 8, 9, and 10 show the time series plots for water, sediment concentration, and mass outflow, respectively, from the artificial VFS. The fact that the curves in Figure 9, b and c, and 10, b and c, generally have a steeper slope than the curves in Figure 9a and Figure 10a suggests that infiltration does play a role in increasing the VFS efficiency temporarily, but as the infiltration rate decreases to a minor proportion of the inflow rate, the overland flow eventually overwhelms the effects of infiltration.

The average observed settling velocity of the low density sediment of 2.7 cm s^{-1} is higher than the reported settling velocities ranging from 0.0004 – 0.076 cm s^{-1} reported by Muñoz-Carpena et al. (1999). Also, the observed particle fall numbers of this study ranged from 37 to 167, while Tollner et al. (1976) report lower particle fall numbers ranging from 0.07 to 50. These comparisons suggest that the experimental conditions for this study, while new based upon the particle settling velocity, did not effectively expand the experimental range of the effective parameters governing sedimentation, namely particle settling velocity (and its impact on particle fall number).

Chapter 4. Conclusions

The infiltration system designed for this experiment functioned well to allow a variable, controllable infiltration rate. Further developments to allow higher infiltration rates (possibly through more infiltration ports or a greater pressure across the needle valve) and lower inflow rates would make the system even more versatile.

The results of the experimental treatments demonstrate that a vegetative filter strip can successfully be used to remove low density sediments from overland flow. Sediment removal efficiency was highly influenced by the flow conditions within the VFS. Comparing these VFS simulation results with modeling results suggests that the original UK model (which is incorporated into VFSMOD) may over predict the effectiveness of a VFS when considering low density sediments, while the modeling equations developed by Deletic may under predict the effectiveness of a VFS. However, it is likely that the very smooth nature of the experimental setup, as demonstrated by the low Manning's n roughness values for the bed and vegetation and the fact that it did not prevent bed load transport, had an (undetermined) negative effect upon the observed VFS efficiency. The UK model was developed with mineral density sediments and accurately predicted the results of the experimental tests with them.

Infiltration was not shown to have a significant effect upon VFS efficiency, but water inflow rate did significantly alter VFS performance. This is likely due to the dominance of overland flow volume to infiltration volume. The highest infiltration volume observed was 18% of the inflow volume, which is much lower than values reported in several field studies (Lim et al., 1998; Coyne et al., 1995; 1998).

No evidence can be found to indicate that other research has investigated low density sediment from a modeling point of view, but other studies have investigated sediments with lower settling velocities than used in this study (Muñoz-Carpena et al., 1999). Due to the relatively large size of the sediments used, the range of particle fall numbers (N_f) in this study was within the range or higher than the particle fall numbers investigated by other researchers (Tollner et al., 1976). Specific areas for further research could include bed load sediment transport and a further study into the effects of infiltration, focusing on higher infiltration as a proportion of inflow.

Chapter 5. Figures

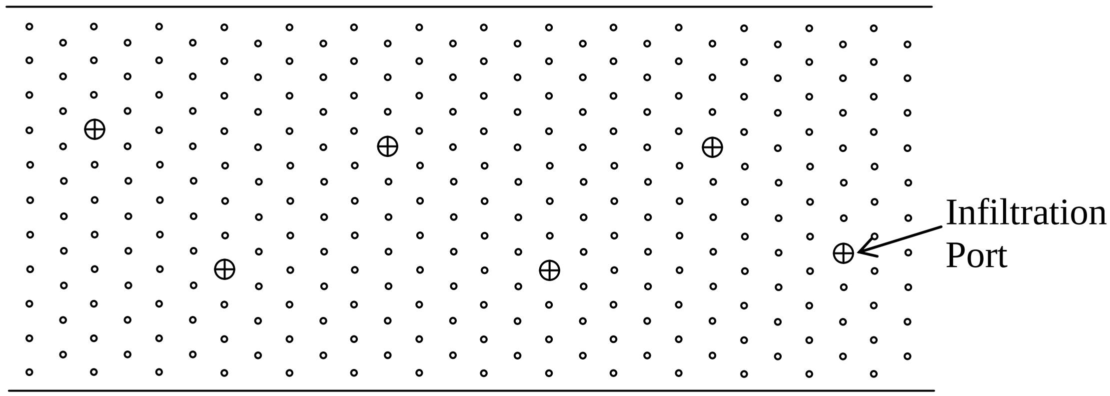

Figure 1. Schematic representation of the layout of the 2.5 cm isometric grid pattern for the cylindrical rods creating the vegetative filter and the distribution of the infiltration ports.

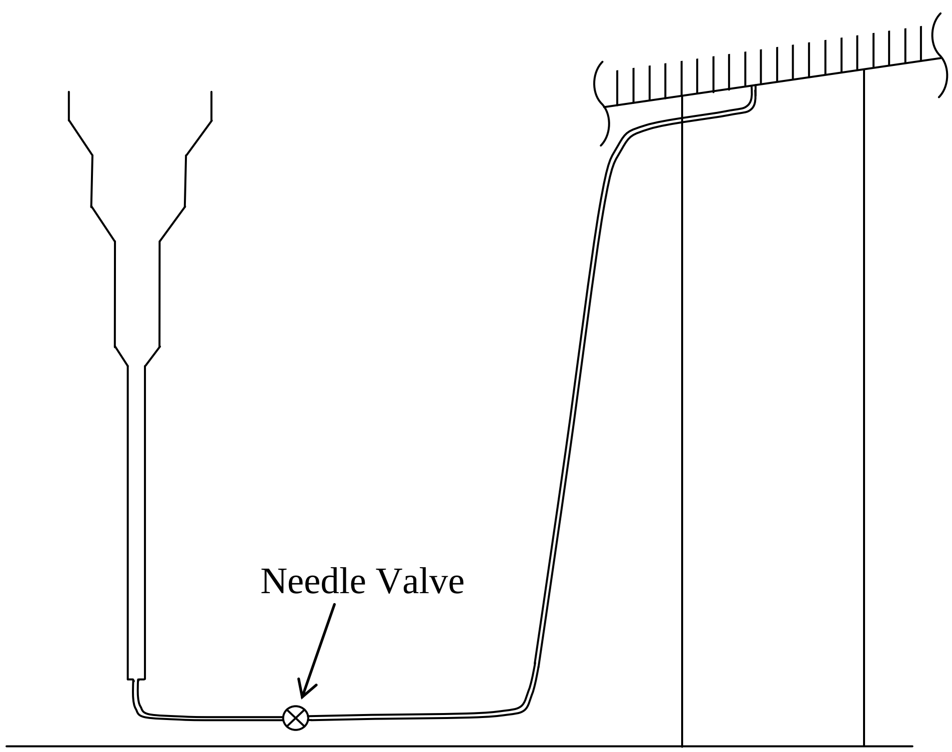

Figure 2. Schematic representation of the infiltration system showing tubing connecting the infiltration port to the inverted cone, through the needle valve.

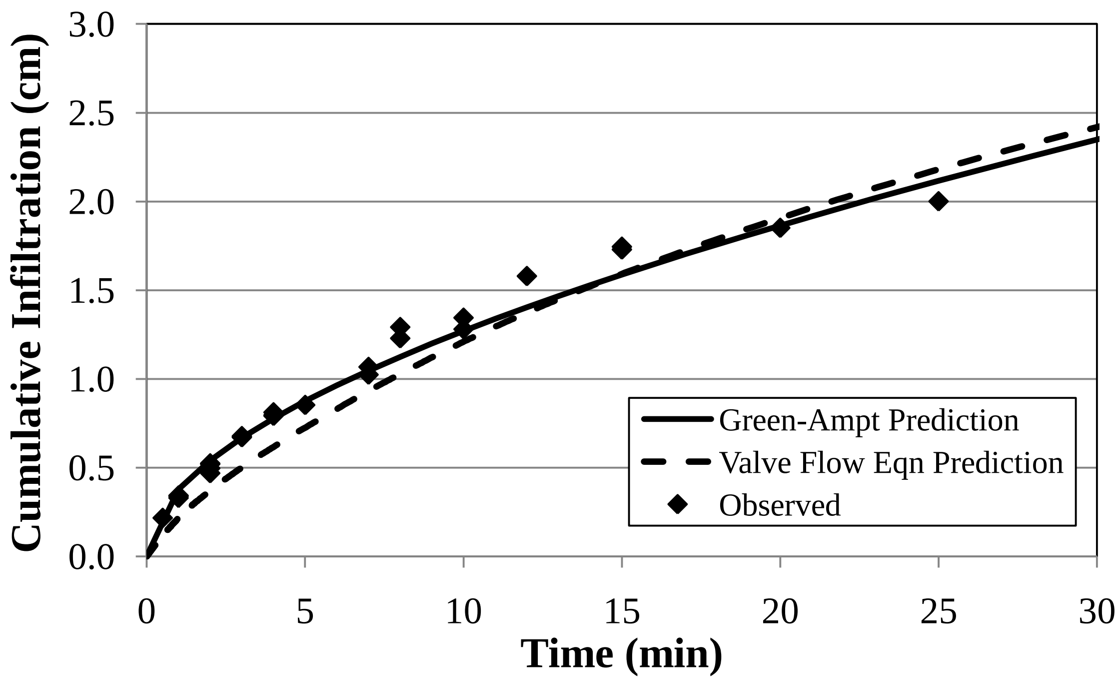

Figure 3. Infiltration system verification showing the observed cumulative infiltration (n = 25), predicted infiltration into the system, and the Green-Ampt model predicted infiltration for the infiltration rate set by Ks = 1.0 cm hr^{-1}.

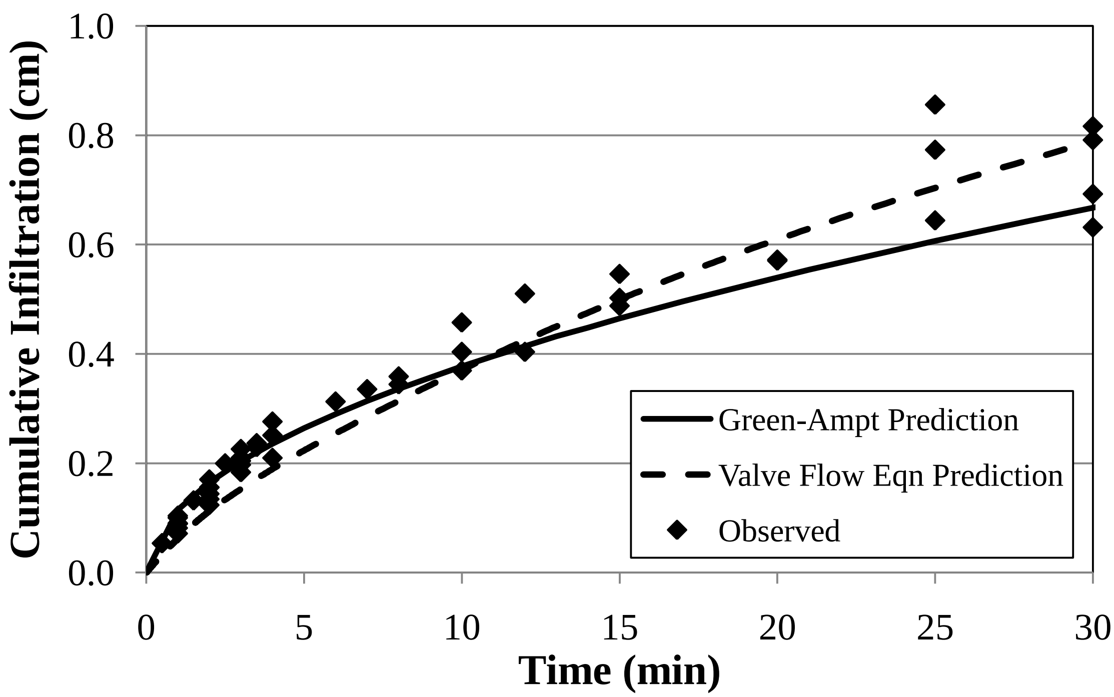

Figure 4. Infiltration system verification showing the observed cumulative infiltration (n = 49), predicted infiltration into the system, and the Green-Ampt model predicted infiltration for the infiltration rate set by Ks = 0.1 cm hr^{-1}.

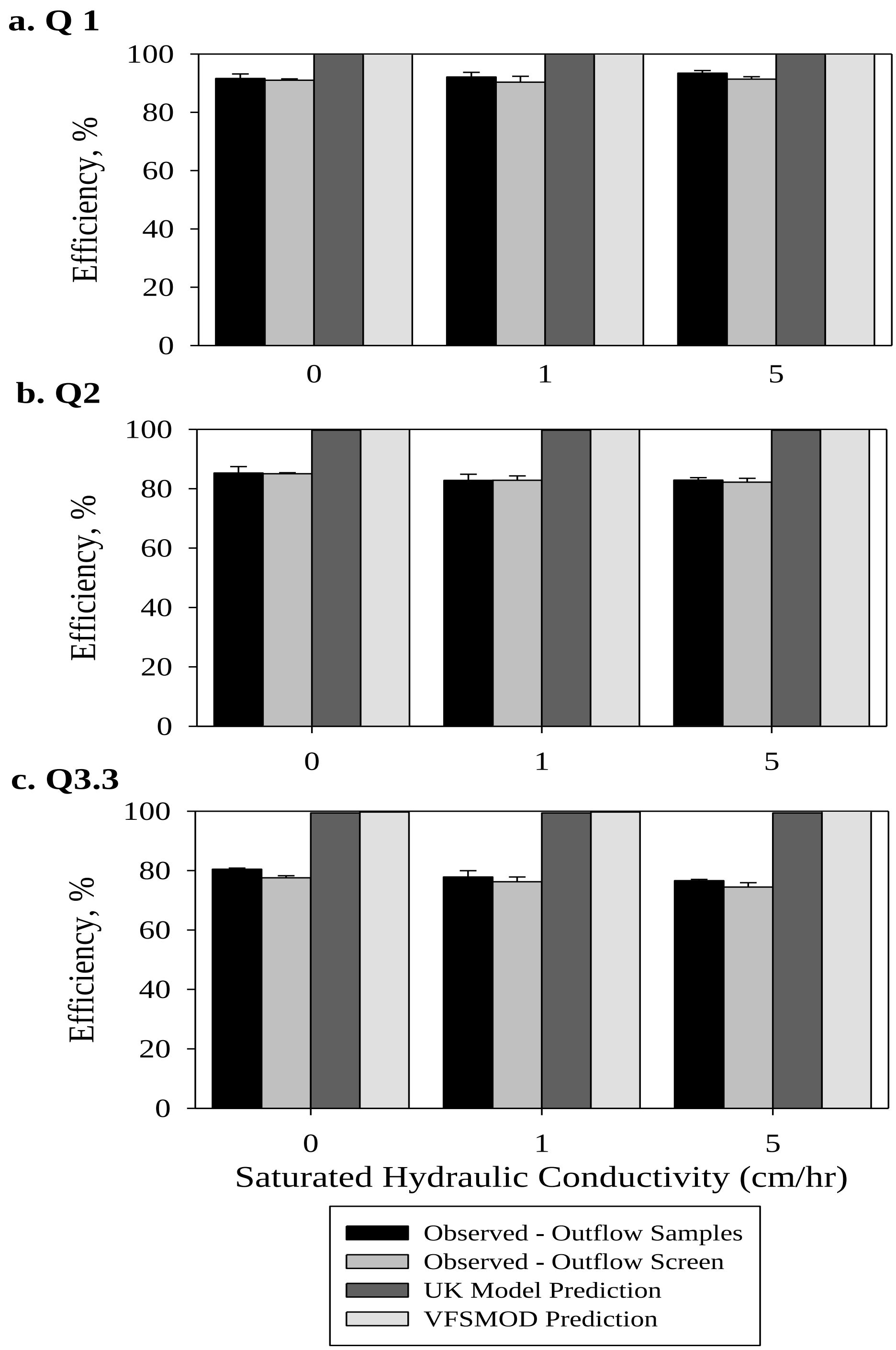

Figure 5. Observed mean filter efficiency (error bar 1 standard deviation) of the artificial VFS and predicted VFS efficiency for the low density sediments for inflow rates of 1, 2, and 3.3 L m^{-1} s^{-1} (Q1, Q2, and Q3.3, respectively).

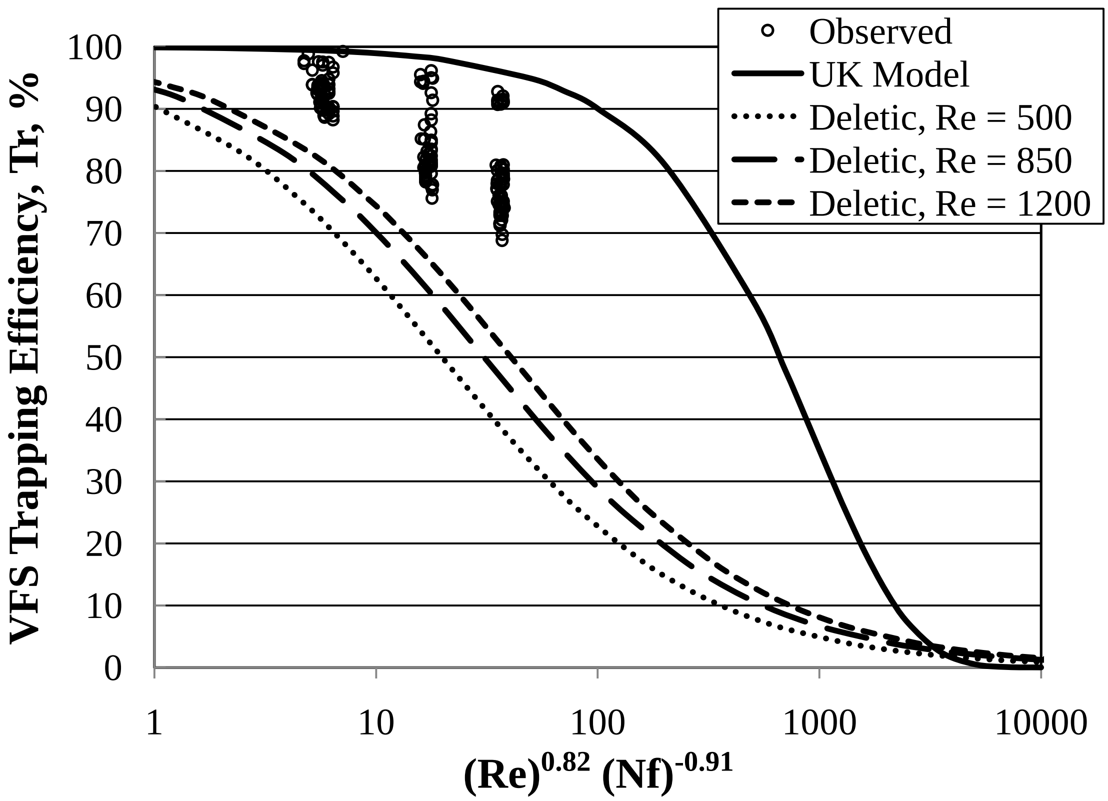

Figure 6. Comparison of VFS trapping efficiency prediction by the UK model, the equation developed by Deletic, and observed results from outflow samples.

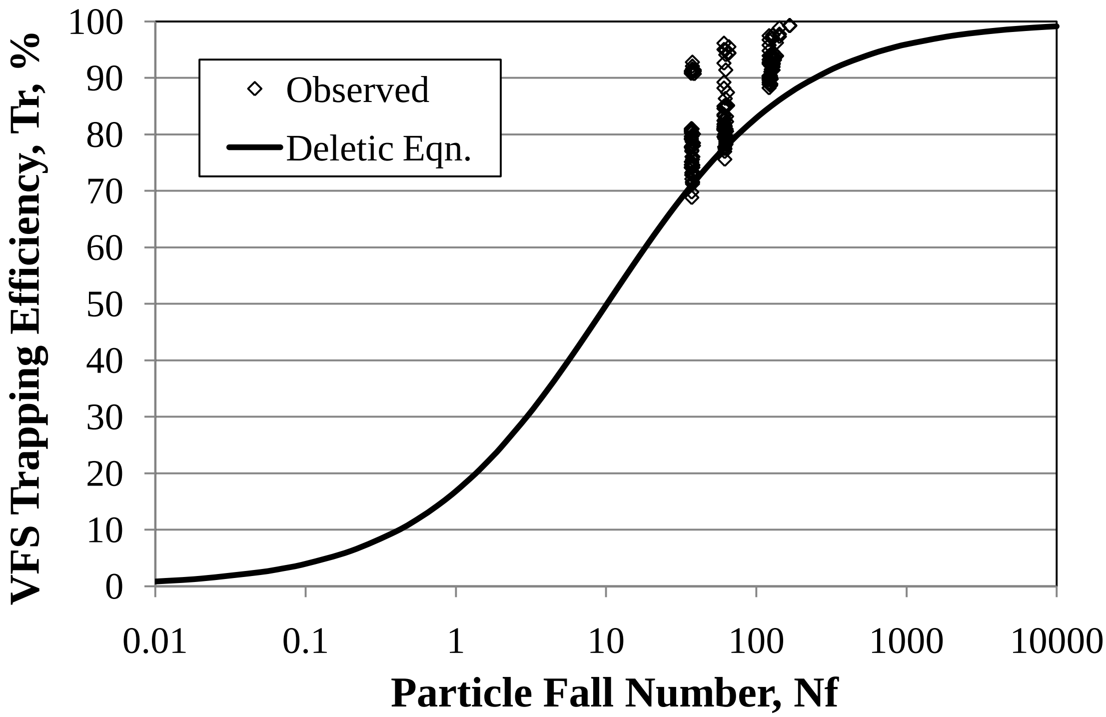

Figure 7. Comparison of VFS trapping efficiency prediction from the equation developed by Deletic and observed results from outflow samples.

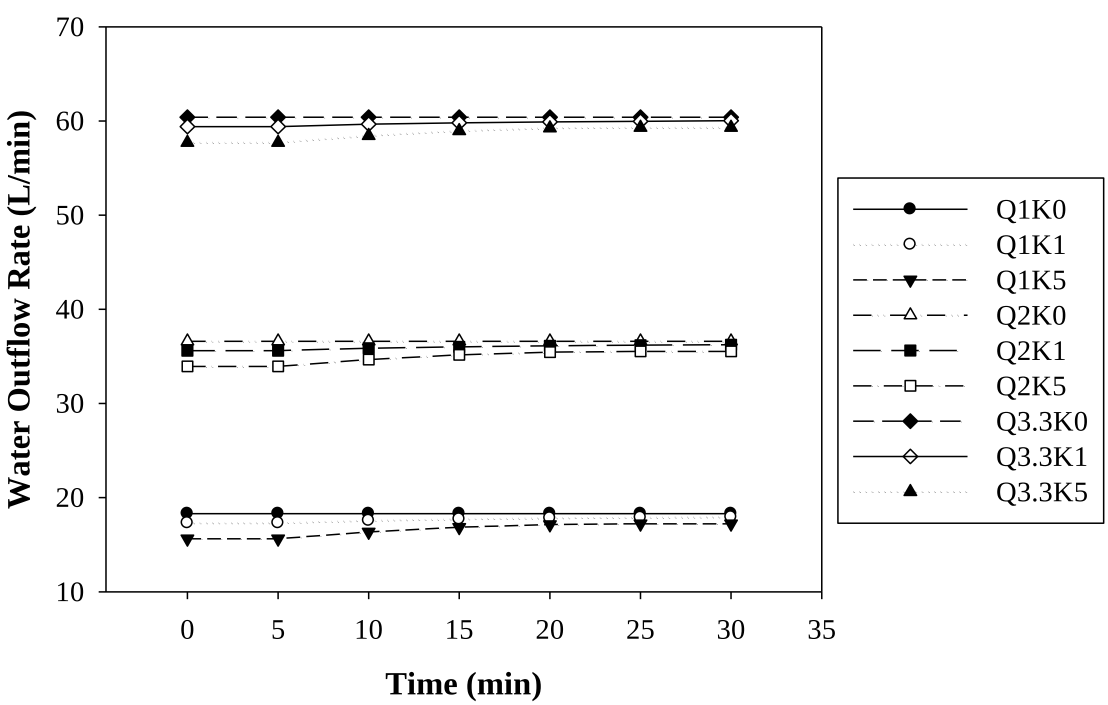

Figure 8. Time series plots of water outflow rate generated by subtracting predicted the infiltration rate from the inflow rate.

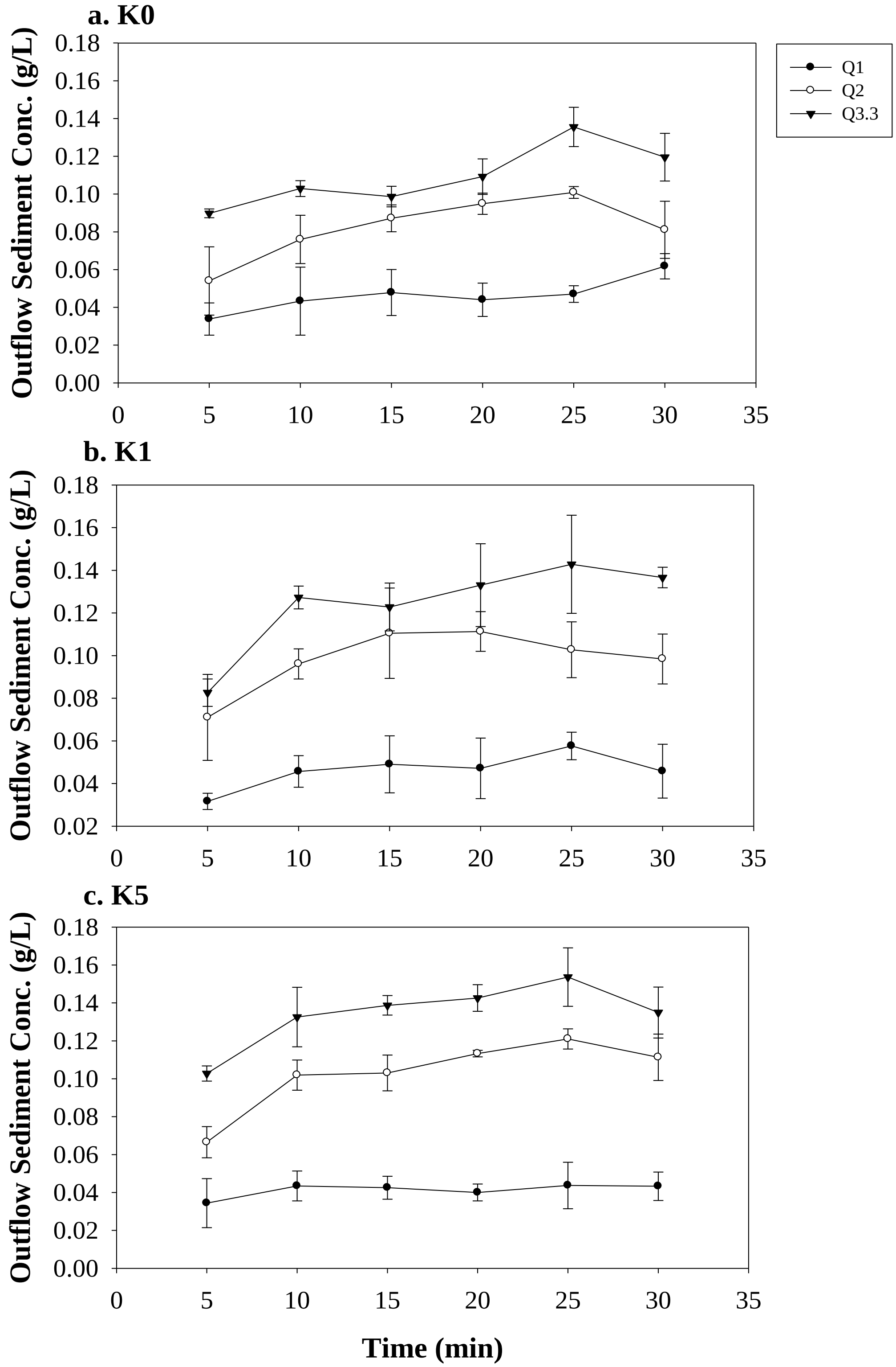

Figure 9. Time series plots of average outflow sediment concentration from grab samples for all tests of low density sediment.

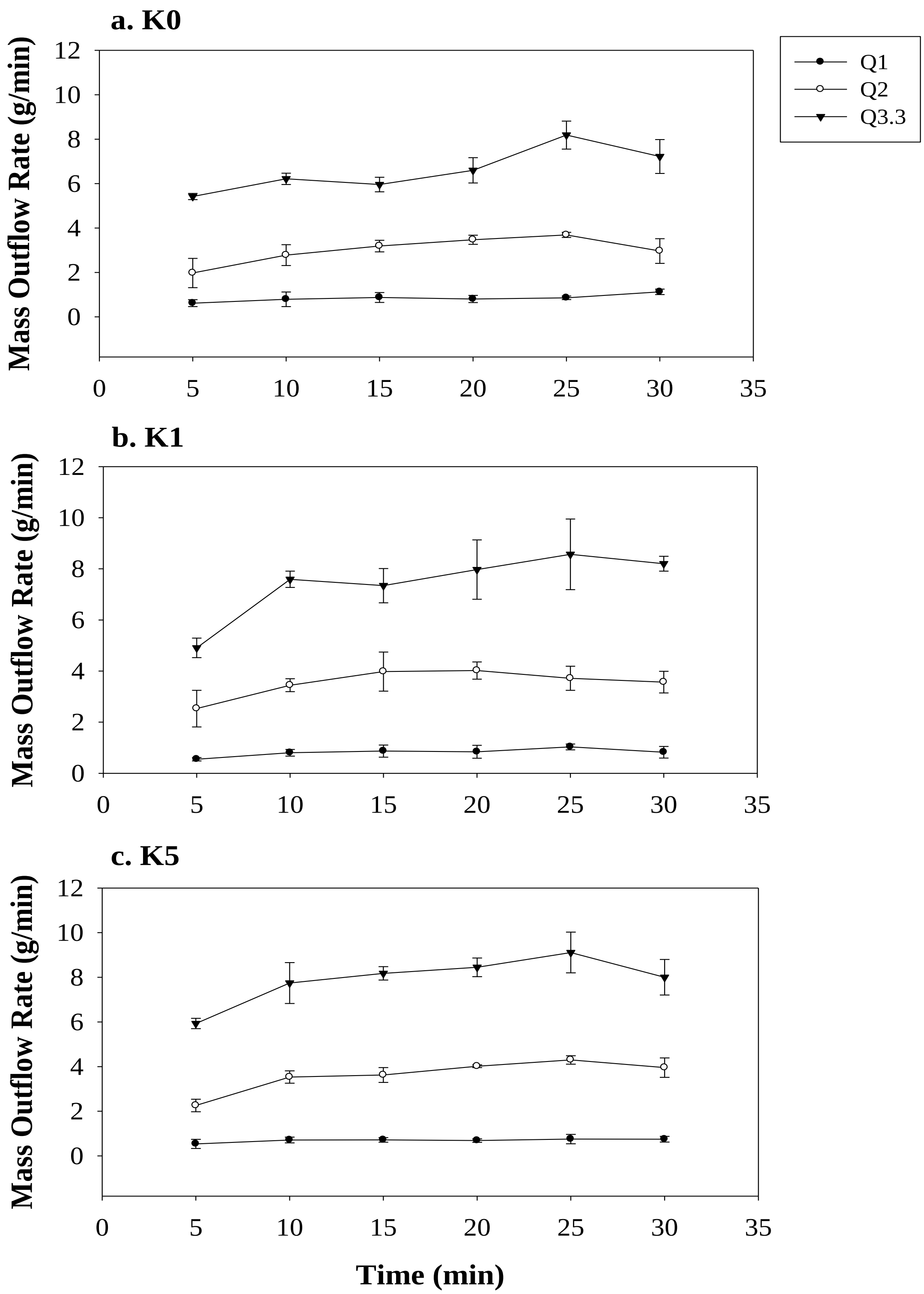

Figure 10. Time series plots of average mass outflow rate calculated from the water outflow rate and average sediment concentrations.

Chapter 6. Tables

Table 1. Components and dimension for the infiltration cones.

Nominal Pipe Size (in)	Inside Diameter (cm)	Pipe Section Length (cm)
1	2.7	76.2
reducer 2 - 1		1.0
2	5.3	12.7
reducer 4 - 2		3.8
4	10.2	10.2
reducer 6 - 4		3.8

Table 2. Experimental parameters, their abbreviations, and the Green – Ampt equation parameters used in VFSMOD and infiltration modeling.

Filter Inflow		Filter Infiltration	
Rate (L m^{-1} s^{-1})	Abbreviation	Sat. Hydraulic Conductivity, Ks (cm hr^{-1})	Abbreviation
1	Q1	0	K0
2	Q2	1	K1
3.3	Q3.3	5	K5

Table 3. VFSMOD input parameters.

Input File	Property	Value	Units
Overland Flow Properties (.ikw)	Segment Properties: Roughness	0.04	
	Number of node in solution domain	57	
	Time weight factor	0.5	
	Number of elemental nodal points	3	
	Petrov-Galerkin Solution	1	
	Courant number	0.8	
	Maximum Iterations	350	
	Output element information	1	
Infiltration - Soil Properties (.iso)	Initial water content	0.28	
	Saturated water content	0.48	
	Maximum surface storage	0	m
	Fraction of filter where ponding is checked	0	
Buffer Vegetation Properties (.igr)	Feedback the change in slope at sediment wedge	0	
	Roughness - Grass Manning's n	0.0072	$s/cm^{1/3}$
	Roughness - Bare surface Manning's n	0.0072	$s/m^{1/3}$
Incoming Sediment Characteristics (.isd)	Incoming sediment particle class	7	
	Sediment particle size, diameter d50	0.03	cm
	Porosity of deposited sediement	0.427	
	Portion of particles with diameter > 0.0037 cm	1	
Storm Hyetograph (.irn)	Time, rainfall rate	0, 0	s, m/s
		1800, 0	
	Maximum rainfall intensity for the storm	0	m/s
Source Area Storm Runoff (.iro)	Source area width	1	m
	Source area flow path length	75	m

Table 4. Summary of the mean and standard deviation of the observed VFS efficiency (%) using two calculation methods as well as the predicted VFS efficiency (%) using and the UK model, VFSMOD software, and the equation developed by Deletic.

Experimental Parameters	Observed VFS Efficiency				UK Model Prediction	VFSMOD Prediction	Deletic Prediction
	Outflow Samples		Outflow Screen				
	Mean	Std Dev	Mean	Std Dev			
Q1K0	91.6	1.6	91.0	0.5	99.7	99.8	84.5
Q1K1	92.1	1.6	90.3	2.0	99.7	99.9	84.5
Q1K5	93.4	0.9	91.4	0.9	99.7	100.0	84.5
Q2K0	85.3	2.2	85.0	0.3	99.3	99.4	77.1
Q2K1	82.8	2.0	82.8	1.5	99.3	99.5	77.1
Q2K5	82.9	0.8	82.2	1.3	99.3	99.6	77.1
Q3.3K0	80.5	0.4	77.6	0.7	98.6	98.8	70.5
Q3.3K1	77.9	2.1	76.2	1.6	98.6	98.9	70.5
Q3.3K5	76.6	0.4	74.5	1.4	98.6	99.1	70.5
Q2K0 Glass Beads	100.0	0.0	100.0	0.0	99.7	100.0	87.1

Table 5. Percentage of inflow water infiltrated through the bed of the VFS.

	Infiltration (% of inflow)		
Inflow	K0	K1	K5
Q1	0	7	18
Q2	0	3	9
Q3.3	0	2	5

References

Abu-Zreig, M., Rudra, R.P., Whiteley, H.R. 2001. Validation of a vegetated filter strip model (VFSMOD). Hydro. Processes 15: 729-742.

Abu-Zreig, M. 2001. Factors affecting sediment trapping in vegetated filter strips: simulation study using VFSMOD. Hydrol. Processes 15: 1477-1488.

ASABE, 2007. Soil and Water Terminology. ASAE S526.3.

Atwill, E.R., Hou, L., Karle, B.M., Harter, T., Tate, K.W., Dahlgren, R. A. 2002. Transport of *Cryptosporidium parvum* oocysts through vegetated buffer strips and estimated filtration efficiency. Appl. and Environ. Microbiol. 68(11): 5517-5527.

Barfield, B.J., Tollner, E.W., Hayes, J.C. 1979. Filtration of sediment by simulated vegetation I. steady-state flow with homogeneous sediment. Transactions of ASAE 22 (3): 540-545.

Blanco-Canqui, H., Gantzer, C.J., Anderson, S.H., Alberts, E.E., Thompson, A.L. 2004. Grass barrier and vegetative filter strip effectiveness in reducing runoff, sediment, nitrogen, and phosphorus loss. Soil Sci. Soc. Am. J. 68: 1670-1678.

Butkus, M.A., Bays, J.T., Labare, M.P. 2003. Influence of surface characteristics on the stability of *Cryptosporidium parvum* oocysts. Appl. and Environ. Microbiol. 69 (7): 3819-3825.

Chow, V.T., Maidment, D.R., Mays, L.W. 1988. Applied Hydrology. McGraw-Hill, New York.

Coyne, M.S., Gilfillen, R.A., Rhodes, R., Blevins, R.L. 1995. Soil and fecal coliform trapping by grass filter strips during simulated rain. J. Soil and Water Conserv. 50 (4): 405-408.

Coyne, M.S., Gilfillen, R.A., Villalba, A., Zhang, Z., Rhodes, R., Dunn, L., Blevins, R.L. 1998. Fecal bacteria trapping by grass filter strips during simulated rain. J. Soil and Water Conserv. 53 (2): 140-145.

Dai, X., Boll, J. 2003. Evaluation of attachment of *Cryptosporidium parvum* and *Giardia lamblia* to soil particles. J. Environ. Qual. 32: 296-304.

Dai, X., Boll, J. 2006. Settling velocity of *Cryptosporidium parvum* and *Giardia lamblia*. Water Research 40 (6): 1321-1325.

Delectic, A. 1999. Sediment behavior in grass filter strips. Water Sci. Tech. 39 (9): 129-136.

Delectic, A. 2001. Modelling of water and sediment transport over grassed areas. J. Hydrology 248: 168-182.

Dillaha, T.A., Sherrard, J.H., Lee, D., Mostaghimi, S., Shanholtz, V.O. 1988. Evaluation of vegetative filter strips as a best management practice for feed lots. J. Water Pollution Control Federation 60 (7): 1231-1238.

Fajardo, J.J., Bauder, J.W., Cash, S.D. 2001. Managing nitrate and bacteria in runoff from livestock confinement areas with vegetative filter strips. J. Soil and Water Conserv. 56 (3) (July 1): 185-191.

Hann, C.T., Barfield, B.J., Hayes, J.C. 1994. Design hydrology and sedimentology for small catchments. Acad. Press, San Diego, USA.

Hayes, J.C., Barfield, B.J., Barnhisel, R.I. 1979. Filtration of sediment by simulated vegetation II. unsteady flow with non-homogeneous sediment. Transactions of ASAE 22: 1063-1067.

Hayes, J.C., Barfield, B.J., Barnhisel, R.I. 1984. Performance of grass filters under laboratory and field conditions. Transactions of ASAE 27 (5): 1321-1331.

Helmers, M.J., Eisenhauer, D.E., Franti, T.G., Dosskey, M.G. 2005a. Modelling sediment trapping in a vegetative filter accounting for converging overland flow. Transactions of ASABE 48 (2): 541-555.

Helmers, M.J., Eisenhauer, D.E., Dosskey, M.G., Franti, T.G., Brotheres, J.M., McCullough, M.C. 2005b. Flow pathways and sediment trapping in a field-scale vegetative filer. Transactions of ASABE 48(3): 955-968.

Helmers, M.J., Eisenhauer, D.E. 2006. Overland flow modeling in a vegetative filter considering non-planar topography and spatial variability of soil hydraulic properties and vegetation density. J. Hydrology 328: 267-282.

Jobling, G.J., Turner, A.K. 1967. The simulation of infiltration for studies in overland flow. Proceedings of the International Hydrological Symposium, Vol. 1. Fort Collins, CO. pp. 203-210.

Lim, T.T., Edwards, D.R., Workman, S.R., Larson, B.T., Dunn, L. 1998. Vegetated filter strip removal of cattle manure constituents in runoff. Transactions of ASAE 41 (5): 1375-1381.

Medema, G.J., Schets, F.M., Teunis, P.F.M., Havelaar, A.H. 1998. Sedimentation of free and attached *Cryptosporidium* oocysts and *Giardia* cysts in water. Appl. and Environ. Microbiol. 64 (11): 4460-4466.

Muñoz-Carpena, R., Parsons, J.E., Gilliam, J.W. 1999. Modeling hydrology and sediment transport in vegetative filter strips. J. Hydrology 214: 111-129.

Nash, I.E., Sutcliffe, J.V. 1970. River flow forecasting through conceptual models. J. Hydrology 10: 282-290.

Searcy, K.E., Packman, A.I., Atwill, E.R., Harter, T. 2005. Association of *Cryptosporidium parvum* with suspended particles: Impact on oocyst sedimentation. Appl. and Environ. Microbiol. 71 (2): 1072-1078.

Searcy, K.E., Packman, A.I., Atwill, E.R., Harter, T. 2006. Deposition of *Cryptosporidium* oocysts in streambeds. Appl. and Environ. Microbiol. 72(3): 1810-1816.

Tate, K.W., Pereira, M.D.G.C., Atwill, E.R. 2004. Efficacy of vegetated buffer strips for retaining *Cryptosporidium parvum*. J Environ. Qual. 33: 2243-2251.

Tate, K.W., Atwill, E.R., Bartolome, J.W., Nader, G. 2006. Significant *Escherichia coli* attenuation by vegetative buffers on annual grasslands. J Environ. Qual. 35: 795-805.

Tollner, E.W., Barfield, B.J., Haan, C.T., Kao, T.Y. 1976. Suspended sediment filtration capacity of simulated vegetation. Transactions of ASAE 19 (4): 678-682.

Tollner, E.W., Barfield, B.J., Vachirakornwatana, C., Haan, C.T. 1977. Sediment deposition patterns in simulated grass filters. Transactions of ASAE 20 (5): 940-944.

Tollner, E.W., Barfield, B.J., Hayes, J.C. 1982. Sedimentology of erect vegetal filters. J. Hydraulics Division, ASCE 108: 1518-1531.

Trask, J.R., Kalita, P.K., Kuhlenschmidt, M.S., Smith, R.D., Funk ,T.L. 2004. Overland and near-surface transport of *Cryptosporidium parvum* from vegetated and nonvegetated surfaces. J. Environ. Qual. 33:984-993.

Tyrrel, S.F., Quinton, J.N. 2003. Overland flow transport of pathogens from agricultural land receiving fecal wastes. J. Applied Microbiol. 94: 87S-93S.

Young, P.L., Komisar, S.J. 2005. Settling behavior of unpurified *Cryptosporidium* oocysts in laboratory settling columns. Environ. Sci. and Tech. 39 (8): 2636-2644.

Appendices

Appendix A. Sample Data Collection Sheet

Date/Time______________________________

Run Parameters

Inflow Rate / Sediment Mixture

1 L/m/s (4.8 gpm)
Feeder: 58 (9.15/45.75)

2 L/m/s (9.7 gpm)
Feeder: 81 (18.3/91.5)

3.3 L/m/s (16.0 gpm)
Feeder: 109 (30.2/150.9)

Conductivity

0 cm/h

1 cm/h (12 valves / 0-1/4-12) 29 min

5 cm/h (24 valves / 1-1/4-0) 18.5 min

Flow

Time	Hose Q (gpm)	D top (cm)	D mid (cm)	D low (cm)
0				
3				
10				
13				
20				
23				
30				

Inflow

Time	Time	Full Mass (g)	Tare (g)			Dry (g)	Tare (g)	
0					Through			
10								
20					Flush			
30								

Outflow

Time	Bottle #	Full Mass (g)	Dish #	Wet Filter	Dry Filter		Comments
5							
10							
15							
20							
25							
30							

Figure A1. Sample flume experiment data collection sheet.

Appendix B. Experimental Data

Table B1. Experimental data for conditions q = 1 L/m/s and K_s = 0 cm/hr.

q	1	L/m/s		K	0	cm/hr
Date	9/23/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	4.8	-----	-----	-----	0.499	-----
3	4.7	1.0	1.1	1.0	-----	-----
5	-----	-----	-----	-----	-----	0.033
10	4.7	-----	-----	-----	0.460	0.040
13	4.8	1.0	1.1	1.1	-----	-----
15	-----	-----	-----	-----	-----	0.059
20	4.8	-----	-----	-----	0.507	0.051
23	4.8	1.1	1.1	1.1	-----	-----
25	-----	-----	-----	-----	-----	0.049
30	4.8	-----	-----	-----	0.506	0.056
Date	9/27/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	4.8	-----	-----	-----	0.489	-----
3	4.8	1.1	1.1	1.1	-----	-----
5	-----	-----	-----	-----	-----	0.026
10	4.8	-----	-----	-----	0.472	0.027
13	4.8	1.1	1.1	1.1	-----	-----
15	-----	-----	-----	-----	-----	0.035
20	4.8	-----	-----	-----	0.485	0.034
23	4.8	1.1	1.1	1.1	-----	-----
25	-----	-----	-----	-----	-----	0.042
30	4.8	-----	-----	-----	0.487	0.061
Date	9/30/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	4.8	-----	-----	-----	0.510	-----
3	4.8	1.1	1.2	1.0	-----	-----
5	-----	-----	-----	-----	-----	0.043
10	4.8	-----	-----	-----	0.477	0.063
13	4.8	1.1	1.2	1.0	-----	-----
15	-----	-----	-----	-----	-----	0.050
20	4.8	-----	-----	-----	0.498	0.047
23	4.8	1.1	1.2	1.0	-----	-----
25	-----	-----	-----	-----	-----	0.050
30	4.8	-----	-----	-----	0.494	0.069

Table B2. Experimental data for conditions q = 1 L/m/s and K_s = 1 cm/hr.

q	1	L/m/s		K	1	cm/hr
Date	9/23/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	4.8	-----	-----	-----	0.498	-----
3	4.8	1.0	1.2	1.1	-----	-----
5	-----	-----	-----	-----	-----	0.036
10	4.7	-----	-----	-----	0.513	0.052
13	4.7	1.1	1.3	1.1	-----	-----
15	-----	-----	-----	-----	-----	0.063
20	4.8	-----	-----	-----	0.497	0.060
23	4.8	1.2	1.3	1.2	-----	-----
25	-----	-----	-----	-----	-----	0.064
30	4.8	-----	-----	-----	0.491	0.058
Date	9/27/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	4.8	-----	-----	-----	0.490	-----
3	4.8	1.0	1.1	1.0	-----	-----
5	-----	-----	-----	-----	-----	0.030
10	4.8	-----	-----	-----	0.511	0.038
13	4.8	1.1	1.1	1.0	-----	-----
15	-----	-----	-----	-----	-----	0.036
20	4.8	-----	-----	-----	0.506	0.032
23	4.8	1.1	1.2	1.1	-----	-----
25	-----	-----	-----	-----	-----	0.051
30	4.8	-----	-----	-----	0.480	0.033
Date	9/30/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	4.8	-----	-----	-----	0.505	-----
3	4.8	1.0	1.0	1.0	-----	-----
5	-----	-----	-----	-----	-----	0.029
10	4.8	-----	-----	-----	0.495	0.047
13	4.8	1.1	1.1	1.0	-----	-----
15	-----	-----	-----	-----	-----	0.049
20	4.8	-----	-----	-----	0.525	0.050
23	4.8	1.1	1.1	1.1	-----	-----
25	-----	-----	-----	-----	-----	0.058
30	4.8	-----	-----	-----	0.514	0.046

Table B3. Experimental data for conditions q = 1 L/m/s and K_s = 5 cm/hr.

q	1	L/m/s		K	5	cm/hr
Date	9/23/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	4.8	-----	-----	-----	0.495	-----
3	4.8	1.0	1.1	1.0	-----	-----
5	-----	-----	-----	-----	-----	0.047
10	4.8	-----	-----	-----	0.506	0.043
13	4.8	1.2	1.2	1.0	-----	-----
15	-----	-----	-----	-----	-----	0.047
20	4.8	-----	-----	-----	0.494	0.045
23	4.8	1.1	1.2	1.1	-----	-----
25	-----	-----	-----	-----	-----	0.049
30	4.8	-----	-----	-----	0.494	0.036
Date	9/27/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	4.8	-----	-----	-----	0.493	-----
3	4.8	1.0	1.0	0.9	-----	-----
5	-----	-----	-----	-----	-----	0.020
10	4.8	-----	-----	-----	0.466	0.036
13	4.8	1.0	1.1	1.0	-----	-----
15	-----	-----	-----	-----	-----	0.047
20	4.8	-----	-----	-----	0.499	0.035
23	4.8	1.1	1.1	1.0	-----	-----
25	-----	-----	-----	-----	-----	0.032
30	4.8	-----	-----	-----	0.504	0.045
Date	9/30/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	4.8	-----	-----	-----	0.517	-----
3	4.8	1.0	1.0	1.0	-----	-----
5	-----	-----	-----	-----	-----	0.039
10	4.8	-----	-----	-----	0.505	0.051
13	4.8	1.0	1.1	1.0	-----	-----
15	-----	-----	-----	-----	-----	0.036
20	4.8	-----	-----	-----	0.464	0.043
23	4.8	1.1	1.2	1.1	-----	-----
25	-----	-----	-----	-----	-----	0.056
30	4.8	-----	-----	-----	0.489	0.050

Table B4. Experimental data for conditions q = 2 L/m/s and K_s = 0 cm/hr.

q	2	L/m/s		K	0	cm/hr
Date	9/24/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.504	-----
3	9.7	1.9	2.0	1.8	-----	-----
5	-----	-----	-----	-----	-----	0.038
10	9.7	-----	-----	-----	0.516	0.069
13	9.7	1.9	2.0	1.8	-----	-----
15	-----	-----	-----	-----	-----	0.081
20	9.7	-----	-----	-----	0.510	0.101
23	9.7	2.0	2.0	1.8	-----	-----
25	-----	-----	-----	-----	-----	0.103
30	9.7	-----	-----	-----	0.498	0.064
Date	9/26/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.504	-----
3	9.7	1.9	2.0	1.8	-----	-----
5	-----	-----	-----	-----	-----	0.074
10	9.7	-----	-----	-----	0.481	0.091
13	9.7	2.0	2.0	1.8	-----	-----
15	-----	-----	-----	-----	-----	0.095
20	9.7	-----	-----	-----	0.476	0.094
23	9.7	2.0	2.0	1.9	-----	-----
25	-----	-----	-----	-----	-----	0.097
30	9.7	-----	-----	-----	0.504	0.091
Date	10/1/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.516	-----
3	9.7	1.9	2.0	1.8	-----	-----
5	-----	-----	-----	-----	-----	0.050
10	9.7	-----	-----	-----	0.497	0.068
13	9.7	1.9	2.0	1.8	-----	-----
15	-----	-----	-----	-----	-----	0.086
20	9.7	-----	-----	-----	0.499	0.090
23	9.7	2.0	2.0	1.8	-----	-----
25	-----	-----	-----	-----	-----	0.102
30	9.7	-----	-----	-----	0.514	0.088

Table B5. Experimental data for conditions q = 2 L/m/s and K_s = 1 cm/hr.

q	2	L/m/s		K	1	cm/hr
Date	9/24/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.501	-----
3	9.7	1.8	2.1	1.9	-----	-----
5	-----	-----	-----	-----	-----	0.064
10	9.7	-----	-----	-----	0.491	0.094
13	9.7	1.9	2.1	1.9	-----	-----
15	-----	-----	-----	-----	-----	0.106
20	9.7	-----	-----	-----	0.509	0.110
23	9.7	2.0	2.1	1.9	-----	-----
25	-----	-----	-----	-----	-----	0.097
30	9.7	-----	-----	-----	0.500	0.089
Date	9/27/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.496	-----
3	9.7	1.8	1.8	1.6	-----	-----
5	-----	-----	-----	-----	-----	0.055
10	9.7	-----	-----	-----	0.528	0.090
13	9.7	1.9	1.9	1.8	-----	-----
15	-----	-----	-----	-----	-----	0.092
20	9.7	-----	-----	-----	0.484	0.103
23	9.7	2.0	2.0	1.8	-----	-----
25	-----	-----	-----	-----	-----	0.093
30	9.7	-----	-----	-----	0.501	0.095
Date	10/1/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.523	-----
3	9.7	1.8	1.9	1.6	-----	-----
5	-----	-----	-----	-----	-----	0.094
10	9.7	-----	-----	-----	0.523	0.104
13	9.7	1.9	1.9	1.7	-----	-----
15	-----	-----	-----	-----	-----	0.133
20	9.7	-----	-----	-----	0.521	0.121
23	9.7	2.0	2.0	1.7	-----	-----
25	-----	-----	-----	-----	-----	0.118
30	9.7	-----	-----	-----	0.509	0.111

Table B6. Experimental data for conditions q = 2 L/m/s and K_s = 5 cm/hr.

q	2	L/m/s		K	5	cm/hr
Date	9/24/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.502	-----
3	9.7	1.9	2.0	1.7	-----	-----
5	-----	-----	-----	-----	-----	0.072
10	9.7	-----	-----	-----	0.507	0.105
13	9.7	1.9	2.1	1.7	-----	-----
15	-----	-----	-----	-----	-----	0.097
20	9.7	-----	-----	-----	0.498	0.114
23	9.7	2.0	2.0	1.8	-----	-----
25	-----	-----	-----	-----	-----	0.126
30	9.7	-----	-----	-----	0.499	0.097
Date	9/27/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.503	-----
3	9.7	1.9	1.8	1.6	-----	-----
5	-----	-----	-----	-----	-----	0.071
10	9.7	-----	-----	-----	0.514	0.108
13	9.7	2.0	2.0	1.8	-----	-----
15	-----	-----	-----	-----	-----	0.114
20	9.7	-----	-----	-----	0.494	0.111
23	9.7	2.0	2.0	1.8	-----	-----
25	-----	-----	-----	-----	-----	0.122
30	9.7	-----	-----	-----	0.505	0.116
Date	10/1/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.507	-----
3	9.7	1.8	1.9	1.7	-----	-----
5	-----	-----	-----	-----	-----	0.057
10	9.7	-----	-----	-----	0.506	0.093
13	9.7	1.9	2.0	1.7	-----	-----
15	-----	-----	-----	-----	-----	0.099
20	9.7	-----	-----	-----	0.520	0.114
23	9.7	2.0	2.0	1.8	-----	-----
25	-----	-----	-----	-----	-----	0.115
30	9.7	-----	-----	-----	0.514	0.120

Table B7. Experimental data for conditions q = 3.3 L/m/s and K_s = 0 cm/hr.

q	3.3	L/m/s		K	0	cm/hr
Date	9/24/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	16.0	-----	-----	-----	0.502	-----
3	16.0	3.0	3.0	2.6	-----	-----
5	-----	-----	-----	-----	-----	0.092
10	16.0	-----	-----	-----	0.489	0.099
13	16.1	3.0	2.9	2.6	-----	-----
15	-----	-----	-----	-----	-----	0.095
20	16.0	-----	-----	-----	0.506	0.099
23	16.0	3.0	2.9	2.6	-----	-----
25	-----	-----	-----	-----	-----	0.124
30	16.0	-----	-----	-----	0.498	0.134
Date	9/25/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	16.0	-----	-----	-----	0.502	-----
3	16.0	3.0	2.9	2.5	-----	-----
5	-----	-----	-----	-----	-----	0.087
10	16.0	-----	-----	-----	0.512	0.102
13	16.0	3.0	2.9	2.5	-----	-----
15	-----	-----	-----	-----	-----	0.105
20	16.0	-----	-----	-----	0.495	0.117
23	16.0	3.0	3.0	2.5	-----	-----
25	-----	-----	-----	-----	-----	0.137
30	16.0	-----	-----	-----	0.502	0.111
Date	10/1/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	16.0	-----	-----	-----	0.540	-----
3	16.0	2.9	3.0	2.5	-----	-----
5	-----	-----	-----	-----	-----	0.090
10	16.0	-----	-----	-----	0.514	0.107
13	16.0	3.0	3.0	2.5	-----	-----
15	-----	-----	-----	-----	-----	0.096
20	16.0	-----	-----	-----	0.514	0.113
23	16.0	3.1	3.0	2.5	-----	-----
25	-----	-----	-----	-----	-----	0.145
30	16.0	-----	-----	-----	0.546	0.113

Table B8. Experimental data for conditions q = 3.3 L/m/s and K_s = 1 cm/hr.

q	3.3	L/m/s		K	1	cm/hr
Date	9/25/2010	Flow Depth (cm) at Specified				
Run Time	Flow Rate	Distance from Inflow End (m)			Sediment Conc. (g/L)	
(min)	(gpm)	1	2.5	4	Inflow	Outflow
0	16.0	-----	-----	-----	0.542	-----
3	16.0	2.9	2.9	2.6	-----	-----
5	-----	-----	-----	-----	-----	0.076
10	16.0	-----	-----	-----	0.490	0.122
13	16.0	3.0	3.0	2.6	-----	-----
15	-----	-----	-----	-----	-----	0.113
20	16.0	-----	-----	-----	0.488	0.112
23	16.0	3.0	3.0	2.7	-----	-----
25	-----	-----	-----	-----	-----	0.123
30	16.0	-----	-----	-----	0.495	0.131
Date	9/25/2010	Flow Depth (cm) at Specified				
Run Time	Flow Rate	Distance from Inflow End (m)			Sediment Conc. (g/L)	
(min)	(gpm)	1	2.5	4	Inflow	Outflow
0	16.0	-----	-----	-----	0.501	-----
3	16.0	2.9	2.8	2.4	-----	-----
5	-----	-----	-----	-----	-----	0.083
10	16.0	-----	-----	-----	0.498	0.127
13	16.0	2.9	2.9	2.5	-----	-----
15	-----	-----	-----	-----	-----	0.120
20	16.0	-----	-----	-----	0.498	0.136
23	16.0	3.1	2.9	2.5	-----	-----
25	-----	-----	-----	-----	-----	0.138
30	16.0	-----	-----	-----	0.499	0.139
Date	9/30/2010	Flow Depth (cm) at Specified				
Run Time	Flow Rate	Distance from Inflow End (m)			Sediment Conc. (g/L)	
(min)	(gpm)	1	2.5	4	Inflow	Outflow
0	16.0	-----	-----	-----	0.505	-----
3	16.0	2.9	2.8	2.6	-----	-----
5	-----	-----	-----	-----	-----	0.089
10	16.0	-----	-----	-----	0.499	0.133
13	16.0	3.0	2.9	2.6	-----	-----
15	-----	-----	-----	-----	-----	0.135
20	16.0	-----	-----	-----	0.507	0.151
23	16.0	3.0	3.0	2.6	-----	-----
25	-----	-----	-----	-----	-----	0.168
30	16.0	-----	-----	-----	0.501	0.140

Table B9. Experimental data for conditions q = 3.3 L/m/s and K_s = 5 cm/hr.

q	3.3	L/m/s		K	5	cm/hr
Date	9/25/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	16.0	-----	-----	-----	0.500	-----
3	16.0	2.8	2.8	2.4	-----	-----
5	-----	-----	-----	-----	-----	0.099
10	16.0	-----	-----	-----	0.510	0.140
13	16.0	3.0	2.9	2.5	-----	-----
15	-----	-----	-----	-----	-----	0.135
20	16.0	-----	-----	-----	0.491	0.148
23	16.0	3.0	2.9	2.5	-----	-----
25	-----	-----	-----	-----	-----	0.137
30	16.0	-----	-----	-----	0.497	0.122
Date	9/25/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	16.0	-----	-----	-----	0.497	-----
3	16.0	2.8	2.8	2.4	-----	-----
5	-----	-----	-----	-----	-----	0.107
10	16.0	-----	-----	-----	0.499	0.114
13	16.0	3.0	2.9	2.5	-----	-----
15	-----	-----	-----	-----	-----	0.145
20	16.0	-----	-----	-----	0.497	0.145
23	16.0	3.0	2.9	2.5	-----	-----
25	-----	-----	-----	-----	-----	0.156
30	16.0	-----	-----	-----	0.502	0.149
Date	9/30/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)			Sediment Conc. (g/L)	
Run Time (min)	Flow Rate (gpm)	1	2.5	4	Inflow	Outflow
0	16.0	-----	-----	-----	0.501	-----
3	16.0	2.8	2.8	2.4	-----	-----
5	-----	-----	-----	-----	-----	0.102
10	16.0	-----	-----	-----	0.515	0.143
13	16.0	3.0	2.9	2.4	-----	-----
15	-----	-----	-----	-----	-----	0.137
20	16.0	-----	-----	-----	0.501	0.135
23	16.0	3.0	2.9	2.5	-----	-----
25	-----	-----	-----	-----	-----	0.167
30	16.0	-----	-----	-----	0.501	0.134

Table B10. Experimental data for conditions q = 2 L/m/s, K_s = 0 cm/hr, and mineral density sediments.

q	2	L/m/s		K	0	cm/hr
Date	10/2/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)				
Run Time (min)	Flow Rate (gpm)				Sediment Conc. (g/L)	
		1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.504	-----
3	9.7	1.9	2.0	1.8	-----	-----
5	-----	-----	-----	-----	-----	0.000
10	9.7	-----	-----	-----	0.491	0.000
13	9.7	1.9	2.0	1.8	-----	-----
15	-----	-----	-----	-----	-----	0.000
20	9.7	-----	-----	-----	0.491	0.000
23	9.7	1.9	2.0	1.8	-----	-----
25	-----	-----	-----	-----	-----	0.000
30	9.7	-----	-----	-----	0.494	0.000
Date	10/2/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)				
Run Time (min)	Flow Rate (gpm)				Sediment Conc. (g/L)	
		1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.563	-----
3	9.7	1.9	2.0	1.8	-----	-----
5	-----	-----	-----	-----	-----	0.000
10	9.7	-----	-----	-----	0.484	0.000
13	9.7	1.9	2.0	1.8	-----	-----
15	-----	-----	-----	-----	-----	0.000
20	9.7	-----	-----	-----	0.485	0.000
23	9.7	1.9	2.0	1.9	-----	-----
25	-----	-----	-----	-----	-----	0.000
30	9.7	-----	-----	-----	0.470	0.000
Date	10/2/2010	Flow Depth (cm) at Specified Distance from Inflow End (m)				
Run Time (min)	Flow Rate (gpm)				Sediment Conc. (g/L)	
		1	2.5	4	Inflow	Outflow
0	9.7	-----	-----	-----	0.497	-----
3	9.7	1.9	2.0	1.8	-----	-----
5	-----	-----	-----	-----	-----	0.001
10	9.7	-----	-----	-----	0.493	0.000
13	9.7	1.9	2.0	1.8	-----	-----
15	-----	-----	-----	-----	-----	0.000
20	9.7	-----	-----	-----	0.488	0.000
23	9.7	1.9	2.0	1.8	-----	-----
25	-----	-----	-----	-----	-----	0.000
30	9.7	-----	-----	-----	0.485	0.000

Appendix C. VFSMOD Simulations

A series of VFS simulations was run using the software program VFSMOD to evaluate the effects of several different parameters on the sediment trapping efficiency of a VFS. Specifically, the parameters: sediment density, size, and concentration; filter length; water inflow rate; and soil saturated hydraulic conductivity were investigated. The specific values investigated are listed in Table C1, and other differences between the flume simulations and these simulations are listed in Table C2. The combinations of variables used provided simulations with particle settling velocities ranging from 0 to 0.9 cm s^{-1}, which was lower than the settling velocities of the particles used in the flume experiments but encompassed the settling velocities of 0.00004 to 0.00008 cm s^{-1} (0.4 – 0.8 µm s^{-1}) reported for protozoan pathogens (Dai and Boll, 2006). VFS sediment removal efficiency was investigated for varying infiltration ratios (proportion of inflow water infiltrating into the soil within the VFS) when considering the results from simulations with particle settling velocities of 0.14 to 0.9 µm s^{-1}, which is similar to those reported for microbial pathogens. The results, shown in Figure C1, indicate that for infiltration ratios less than 0.65 the VFS efficiency is very low, with a mean of 3.9% (n = 216). This provides further validation of the conclusion of Tyrrel and Quinton (2003) that without other mechanisms for microbial pathogen removal or complete infiltration of inflow water a VFS does not function to remove these particles from overland flow.

After extensive analysis of the model outputs, some patterns were discernable within the data set, but no underlying ties were discovered to explain the observed patterns. Further research is needed to determine any undiscovered relations between the predicted VFS efficiency and other factors such as infiltration and sediment properties.

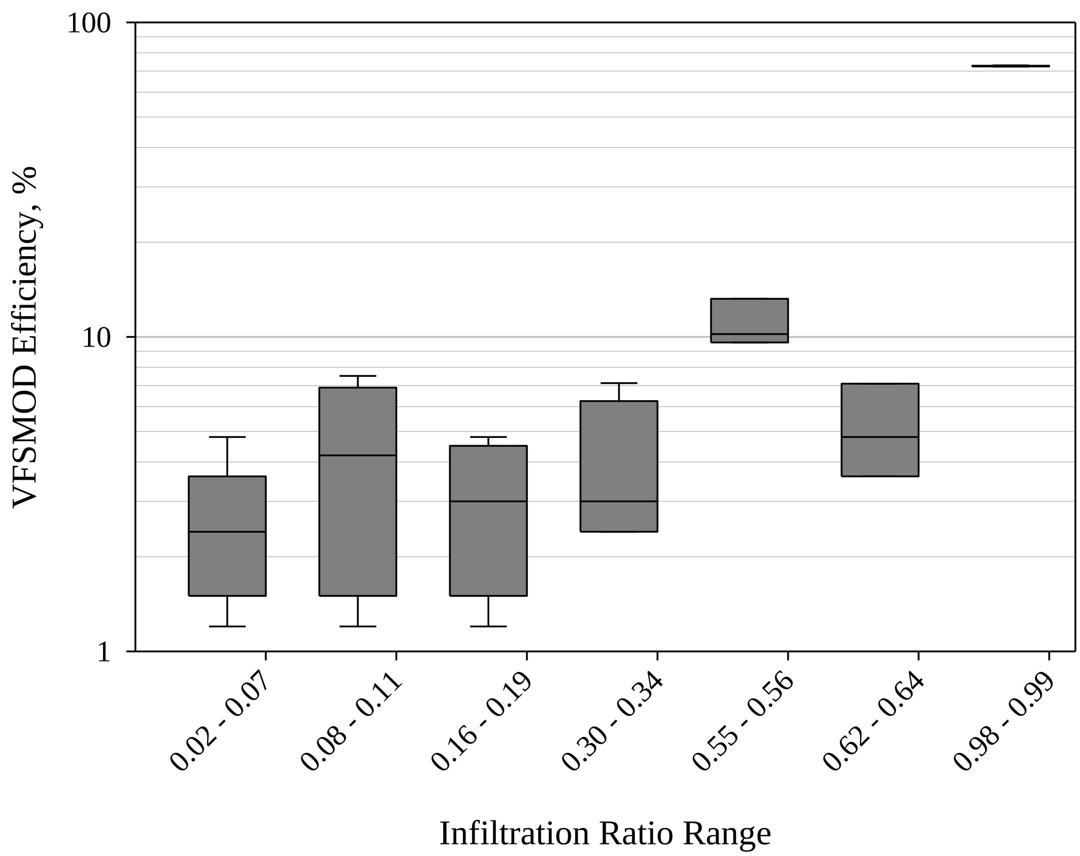

Figure C1. VFS sediment removal efficiency grouped by infiltration ratio for particles with a settling velocity in the range 0.14 – 0.9 µm s^{-1}. Boxes encompass the 25^{th} to the 75^{th} percentile with the median indicated and error bars showing the 10^{th} and 90^{th} percentiles.

Table C1. Variable values investigated with VFSMOD simulations.

Filter Length (m)	Inflow Rate (m^3/s)	Saturated Hydraulic Conductivity (cm/hr)
5	0.001	0.1
10	0.002	1
20	0.003	10
Sediment Properties		
Density (g/cm^3)	Diameter (cm)	Concentration (g/cm^3)
1.25	0.00001	0.0001
2.0	0.0001	0.001
2.65	0.001	0.01
	0.01	

Table C2. VFSMOD parameters for investigative simulations.

Input File	Property	Value	Units
Buffer Vegetation Properties (.igr)	Spacing for grass stems	1.6	cm
	Height of grass	30	cm
	Roughness - grass Manning's n	0.012	s/cm$^{1/3}$
	Roughness - bare surface Manning's n	0.04	s/m$^{1/3}$
Incoming Sediment Characteristics (.isd)	Portion of particles with diameter > 0.0037 cm	dependant upon particle size	
Storm Hyetograph (.irn)	Time, rainfall rate	0, 0.000017225	s, m/s
		3600, 0.000017225	s, m/s
	Maximum rainfall intensity	0.000017225	m/s
Source Area Storm Runoff (.iro)	Time, runoff rate	1800, inflow rate	s, m^3/s
		10800, inflow rate	
	Peak flow of incoming hydrograph	inflow rate	m^3/s